RESEARCH DEPARTMENT

THE COLOUR RESPONSE OF MONOCHROME TELEVISION CAMERA TUBES

Report No. T-081

(1962/2)

THE BRITISH BROADCASTING CORPORATION
ENGINEERING DIVISION

RESEARCH DEPARTMENT

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D. Maurice

C.B.B. Wood (D. Maurice)

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SUMMARY

This report describes a number of subjective tests which were carried out to determine viewers' preferences and tolerances for relative colour response in television cameras. Relative colour response is a term used to describe the characteristic by which the camera portrays the colours of the original scene as simple luminances in the black-and-white television image.

Other tests were conducted to determine the viewers' awareness of deliberate alterations made in the colour response of a television camera. This is an important aspect of the investigation, since experience has shown that closer limits of tolerance must be imposed if cameras used in the same television production are to give acceptably well-matched monochrome versions of the same scene. It was found that the type of subject matter placed before the camera has a substantial bearing upon the required accuracy of colour response characteristic.

1. INTRODUCTION

The response of photoelectric materials to radiation stimuli of differing wavelengths varies considerably, not only from one material to another but also during the repetitive manufacture of a specific device. A selection of typical responses given by some of the photosensitive materials which have been used in television camera tubes is shown in Fig. 1.

Early television camera tubes, such as the "Standard Emitron"[1] used a photosensitive surface which was prepared from a very thin, almost invisible film of metallic silver vacuum-deposited on a sheet of mica. This film was then oxidised and finally activated to maximum sensitivity by the introduction of small quantities of caesium which, when heated, will react with the silver oxide. The colour response of this material may, with slight alterations in manufacturing methods, vary from the curve (marked "Earliest Camera Tubes") shown in Fig. 1 to that marked "Standard Emitron". Very early (pre-war) camera tubes tended towards the former curve and were much too sensitive to various shades of red in the scene. The response to infra-red radiation was also an embarrassment since it was outside the colour-corrected range of the lens, and gave rise to camera focusing difficulties.

With the introduction of other camera tubes, notably the C.P.S. Emitron,[2] the semi-transparent antimony/caesium photocathode came into general use. This material has a strong response in the blue-green region (see Fig. 1) but is considered

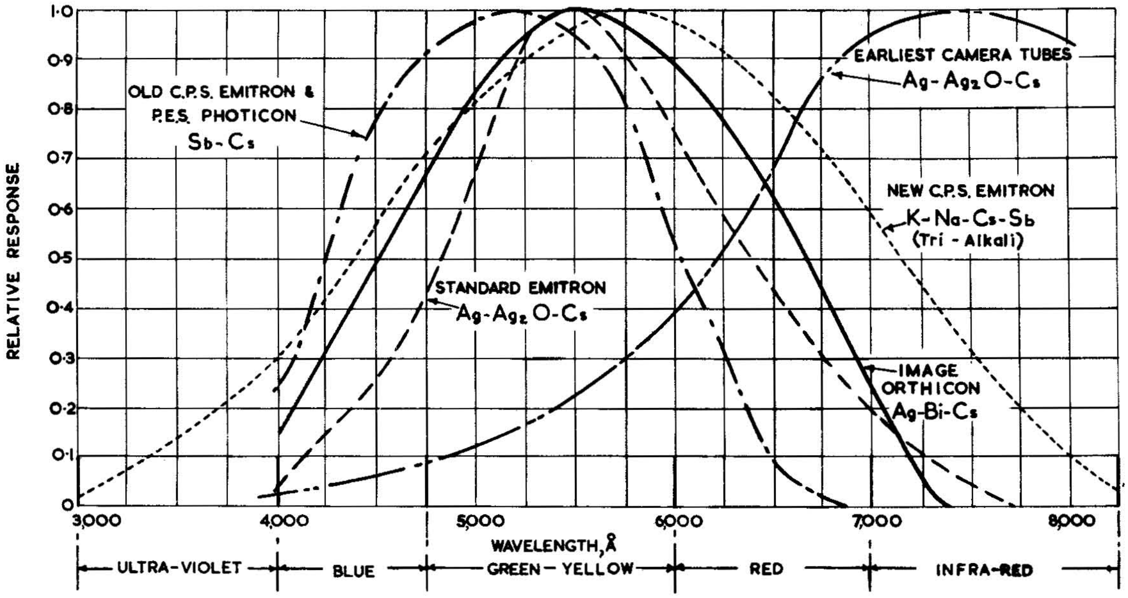


Fig. 1 - Typical responses of photosensitive materials used in television cameras (Tungsten illuminant)

by many users to have insufficient red response for ideal studio use. Nevertheless P.E.S. Photicons using this photocathode material have been favoured for news studio work where the principal subject matter is the male face. More recent C.P.S. Emitrons use what is known as the tri-alkali photocathode (potassium/sodium/caesium/antimony). This material has very high overall sensitivity but its colour response extends over a very broad band and it is thought in some quarters to have swung, once more, too far towards red sensitivity.

The image orthicon camera tube uses a silver/bismuth/caesium photocathode which thus becomes the most widely used material at present. Its colour response has no very pronounced shortcomings and is generally agreed by operational and production staff to correspond more nearly to the optimum characteristic than other materials. It was therefore an obvious choice for the camera tube to be used in the experiments to be described in the following pages, and the investigation was carried out by making variations from the normal response of silver/bismuth/caesium rather than by the use of other photocathode materials.

A difficulty which immediately presents itself in an investigation of this kind is that from an infinite variety of response characteristics it is possible to examine only a few. The choice and variety of responses available for comparison was in this case governed by the range of gelatin colour filters commercially available since the experiments were carried out by taking an image orthicon of "average" colour response which was then modified by placing suitable colour filters in the light path.

2. THE "PHOTOPIC CURVE"

It is well known that the sensitivity of the human eye to radiant energy depends upon wavelength, and an internationally agreed standard response, sometimes called the "Photopic Curve", shows the relative luminous efficiency to radiation at normal brightness levels. The relationships do not hold for very low brightness levels, where the relative sensitivity of the eye to red becomes much reduced, and relative sensitivity to blue increases: this is known as the Purkinje effect.

The accepted values of relative luminance for photopic vision are based mainly upon the published results of five independent investigations.[3] Of these, three used a flicker-photometer method in which equal-area fields of two dissimilar colours were compared in rapid alternations while their radiance was adjusted for minimum luminosity difference. The remaining two investigations used a "step by step" method in which two adjacent areas of a field were simultaneously irradiated by monochromatic light of slightly different wavelengths. The radiance of the second colour was adjusted for minimum luminosity difference from the first, and then a third colour was compared with the second and so on until the entire visible spectrum had been explored.

In the flicker method the colours may be widely different, since colour fusion takes place in the eye at much lower frequencies of alternation than that at which the flicker disappears, but in the adjacent-area method the steps must be small if a satisfactory balance of luminosity is to be achieved. Direct comparison of colours with neutral grey gives very inconsistent results.

In viewing the natural scene the eye always has the advantage of both colour contrast and luminance contrast, and therefore the luminance efficiency curve alone is not necessarily a criterion for the black-and-white response of a television camera tube. Clearly there cannot be one truly ideal colour response for the monochrome television camera, since, no matter what the response, a coloured scene could always be contrived in which (to the camera) there were no luminance contrasts at all and the monochrome version would be completely blank or uniformly luminous. The optimum response will be that which gives the most pleasing monochrome rendering of most normal scenes and this is not necessarily given by objective accuracy; indeed, first thoughts on the subject might indicate that it would be desirable to enhance the luminance contrast in order to compensate for the loss of another dimension (colour). This leads to the probability that every scene may require a different colour response for optimum black-and-white portrayal.

3. THE SCOPE OF THE INVESTIGATION

It has already been indicated that some camera tubes have, in the past, found favour or otherwise on account of their colour response. From time to time tests have been conducted in studios in an attempt to find the "ideal" response on a subjective basis, but since these tests have usually been restricted to single experiments using only one type of subject matter, the results have been far from conclusive and often contradictory. The consensus of opinion of producers and operational personnel, after a long period of experience with a given photocathode material, is a reliable guide but an operational opinion concerning the more subtle variations due to the manufacturing spread in a single type of tube is not available, since the precise characteristics of individual tubes are not known to the studio personnel who use them.

The experiments to be described here were started in the belief that a fairly simple and straightforward answer would be forthcoming, but as the work progressed it became increasingly obvious that present opinions were in need of qualification.

In planning the investigations it was decided that a sufficiently wide variety of colour response characteristics must be independently investigated in the following different applications.

1. Outdoor scenes illuminated by daylight.
2. Faces (male and female) illuminated by tungsten studio lighting.
3. Pigments and dyestuffs illuminated by tungsten studio lighting.

Other combinations which suggested themselves were thought to be of less importance than the three mentioned above.

Once the most critical and sensitive form of subject matter had been established, the next step would be to determine the degree of alteration of colour response necessary to produce a noticeable change in the monochrome representation of it. This would then indicate the tolerance which might be permitted for camera tubes intended to be placed in general service, taking into account the likelihood that they would be used in conjunction with other camera tubes on the same location.

If such tolerances proved impossibly restrictive, then some grading scheme would have to be recommended so that only like tubes were used together.

4. THE COLOUR RESPONSE OF A TYPICAL IMAGE ORTHICON COMPARED WITH THAT OF THE EYE

The measured response of a typical 4½ in image orthicon tube to light of equal radiance at all wavelengths is shown in Fig. 2. The tube was also examined

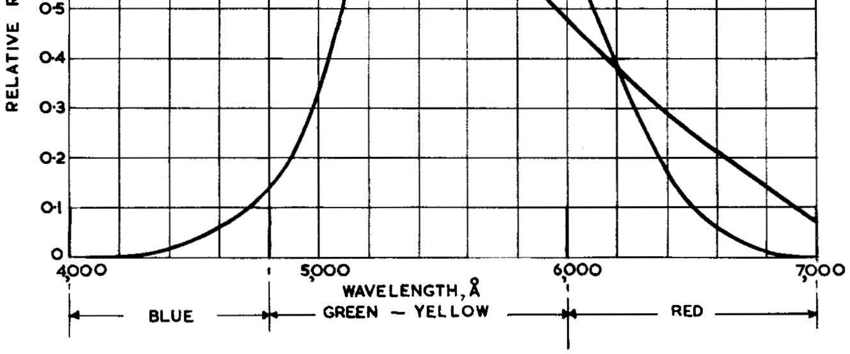


Fig. 2 - Typical image orthicon response to equi-energy illumination (Approximately indicates outdoor conditions)

for response to stimuli in the infra-red regions in case any subsidiary peaks should be present, but the output continued to decrease as the wavelength of the incident radiance was increased from 6,800 Å to 10,000 Å.

For convenience, the curve of relative luminous efficiency of the eye is also shown, and it will be seen that the image orthicon is very dissimilar to the eye in its response to equi-energy illumination (sunlight could be considered to be of approximately equi-energy distribution). Where, however, the image orthicon is used with incandescent tungsten illumination, as in television studios, the state of affairs changes considerably because of the non-uniform distribution of energy in tungsten light. This distribution is shown in Fig. 3, while Fig. 4 shows the two responses of Fig. 2 multiplied by the function in Fig. 3.

The eye is well known to have the ability to make subjective correction for a very wide range of illuminants (e.g. a white card by tungsten illumination is accepted as white although the same spectral distribution would appear to be very yellow under daylight conditions) and there seems little point in making more than a cursory comparison between the colour responses of camera tubes and the eye. The camera is from time to time required to portray authentic outdoor scenes, studio scenes purporting to be outdoors, and interior scenes, all of which might be illuminated by daylight, arclight, tungsten or combinations of these illuminants, and it will do so entirely objectively. The criterion of success is that the combination of scene design and lighting in conjunction with the tube response gives an acceptable black-and-white image of what the original scene was supposed to be.

5. CONTROL OF COLOUR RESPONSE DURING THE EXPERIMENT

The camera tube used for the experiment was a 4½ in image orthicon type P.822 No. 8565 fitted in a Marconi Mk. III camera. It was established that the apparatus was correctly lined-up and in proper working order.

The colour-response of the camera tube had been measured with great care, and by three different methods.

(1) The standard Research Department colour response test apparatus, using narrow-cut gelatin filters to be matched in density by crossed neutral density wedges.
(2) The same test apparatus but using the newly-available metal dielectric filters having very narrow passbands.
(3) By means of a "Unicam" Monochromator.

Tests (1) and (2) have to be made with the tube installed in a camera and working normally, while test (3) investigates only the photocathode and uses the tube as a simple photocell. Very close agreement was obtained with all three methods, and it was also established that the tube concerned was a normal specimen, typical of many tubes measured in the past.

A number of gelatin colour filters were then prepared, each designed to modify the colour response of the tube by a controlled amount. One series of filters was selected to raise or lower the relative response of the camera to radia-

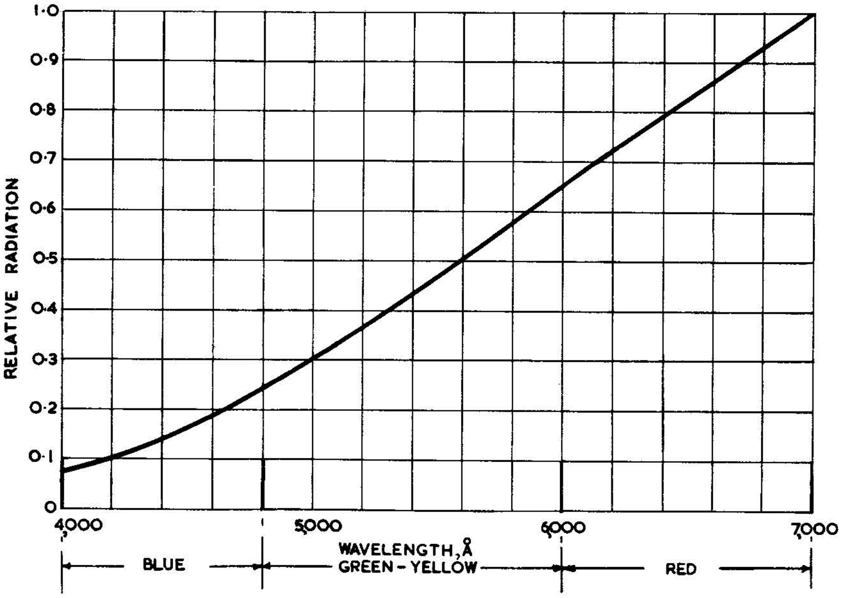


Fig. 3 - Energy distribution of radiation from tungsten filament (2700° K)

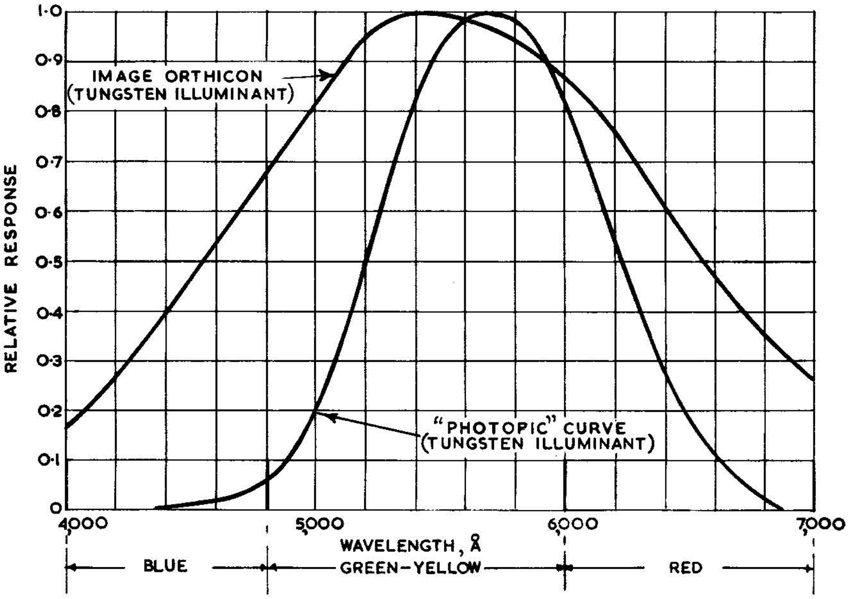


Fig. 4 - Typical image orthicon response to tungsten illumination (2700° K)

tions of wavelength between 6,200 Å and 7,000 Å (the "red" parts of the spectrum) without substantially modifying the relative response to other colours. Another series of filters was provided to give variation of the relative response to radiation of wavelength between 4,000 Å and 4,800 Å (the "blue" parts of the spectrum), again without substantial modification of the relative response to other colours.

In every test made with tungsten illumination, a small light-box, producing a standardised sample of "peak white" Illuminant A, was included in the scene and the lens iris of the camera was adjusted until this object gave a standard signal voltage output. In this way the insertion loss due to the filters was removed.

The variously modified colour responses of the image orthicon (No. 8565) used for the tests are shown in Figs. 5 and 7 (pages 8 and 10).

It will be appreciated that it is not always possible to produce a modifying filter which leaves the main part of the response characteristic completely unchanged. Conditions (1) and (2) of Fig. 7 (page 10) are examples of the introduction of a "dip" at 5,600 Å which would have been avoided if possible. It is however, unlikely to have influenced the results to any significant extent.

In order to make the tests as critical as possible, the observer was able to see the original scene at the same time as the monochrome television version. The television camera was placed alongside the observer, and the television picture was displayed on a 21 in monitor adjacent to the original scene. Where the procedure was applicable, observers were asked to score the acceptability of each black-and-white version as follows:

Very good	(3 points)
Reasonably good	(2 points)
Rather poor	(1 point)
Very poor	(0 points)

The various colour response conditions were presented in random order with many repeats.

6. INITIAL TESTS TO DETERMINE THE ACCEPTABILITY OF VARIOUS COLOUR RESPONSES

6.1. Television Cameras Outdoors

The first investigation was to find the desired colour response when the image orthicon is used outdoors, and is, therefore, "seeing" light of roughly equi-energy distribution.

The television camera was set up to view a number of natural outdoor scenes in weather conditions varying from bright sunlight to dull and cloudy; the scenes included modern domestic architecture, trees, lawns, a roadway with some vehicular traffic, and pedestrians. The observers were able to see the natural scene from a window and then, after a suitable period for adaptation, to appraise the black-and-white television version of the scene with freedom to refer back to the original scene whenever they wished.

After a few preliminary tests in which only minor changes of colour response were shown, it became obvious that this application of the image orthicon does not call for any high degree of accuracy in colour response. A special colour filter was then made up to modify the characteristic from that of the typical silver/bismuth/caesium to something even less red-sensitive than the typical antimony/caesium response. Another filter was chosen to give a very pronounced sensitivity to reds in the scene although it could hardly be described as an approximation to the basic silver/silver oxide/caesium response. It was thus possible to make a fairly drastic change in response, more or less representing the extremes encountered throughout the history of television cameras.

The overall response to equi-energy radiation of the image orthicon plus the modifying filters is shown in Fig. 5.

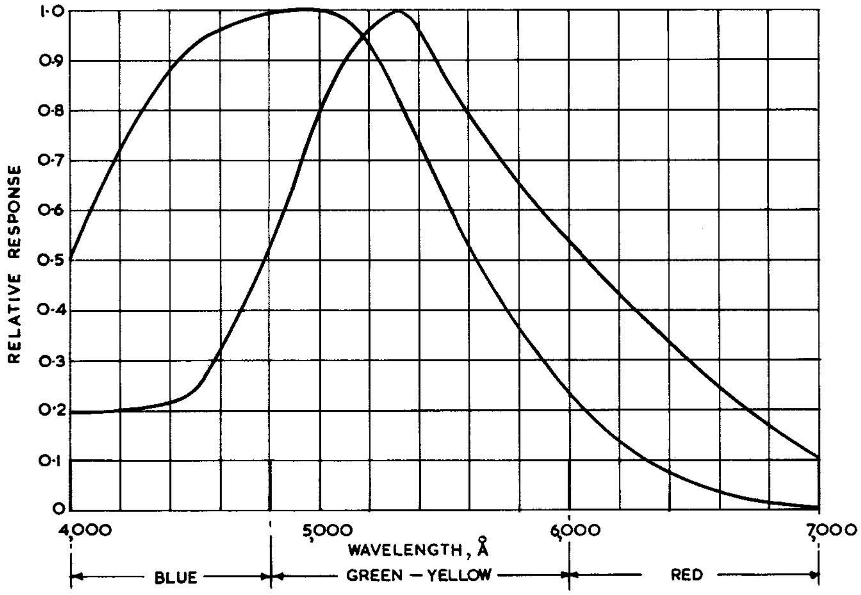


Fig. 5 - Extremes of modified response to daylight illumination

Only twelve observers were used in this test but these were all skilled television engineers, extremely critical of picture quality, and when the filters were changed from one extreme to the other, only one of the twelve noticed any change in any of the black-and-white television versions of the variety of outdoor scenes already mentioned. Since the extremes chosen were equal to the responses given by other photocathode materials known to be less satisfactory in more exacting applications and far outside the spread of the silver/bismuth/caesium response, the inference is that *any normal image orthicon will satisfy ordinary outdoor television requirements, in so far as colour response is concerned.*

It is however interesting to note that for certain outside broadcast applications[4] it has been found desirable to introduce a gross distortion of the colour response of the image orthicon in order to enhance the contrast between the object of interest and the background. These are the cases in which the natural scene presents to the eye a satisfactory colour contrast but has very little luminance contrast. Typical response to daylight of an image orthicon, modified by those colour filters which have been recommended for suitably distorting its colour response, is shown in Fig. 6.

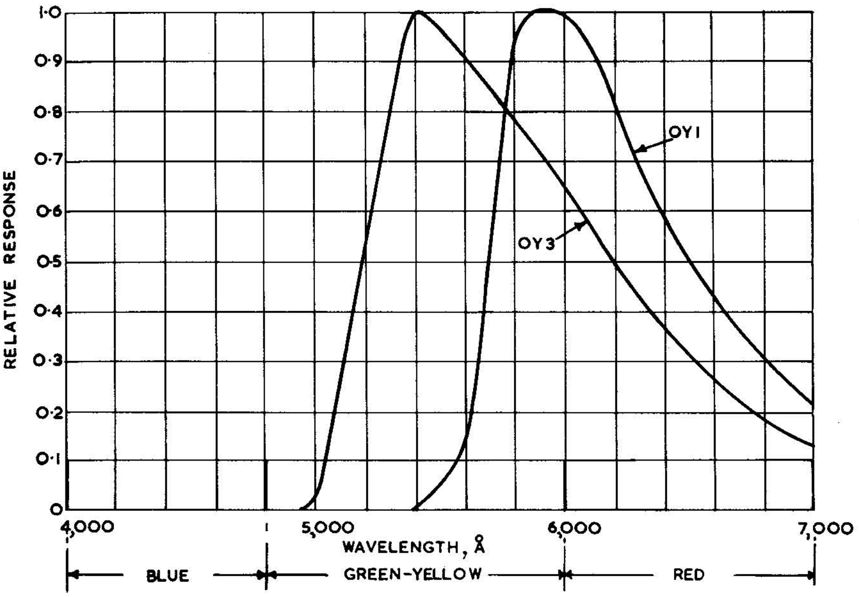


Fig. 6 - Typical image orthicon response to daylight when used with colour filters OY1 and OY2

6.2. Studio Television — The Preferred Colour Response for Portraiture

It was expected that the next part of the investigation might yield a well-defined preference for some particular colour response since there have in the past been many complaints of incorrect tonal reproduction of human faces when illuminated by studio tungsten lighting. It was, however, again found that fairly drastic changes in the colour response were necessary before observers detected any errors in the black-and-white television portrait. It should be emphasised that this particular test was concerned only with observers' preferences for colour response and was not attempting to define noticeable changes which occur when rapid cuts are made from one camera to another.

The test was carried out in two parts using observers drawn from two distinct groups. The first group consisted of twenty-two television engineers, experienced in subjective testing and aware of the purposes of the experiment. The second group consisted of twenty-seven people not familiar with the technology of colour or television e.g., drawing office and workshops staff.

In either test the "models" were seen in medium closeup by television, and were also visible to the observers directly, since these (in batches of about four) were grouped around the television camera. A number of models were used, male and female, of fair and dark complexions: all were portrayed against a background of light, desaturated, cream-coloured distemper. Ordinary makeup was worn by most of the female models, none by the men.

The twenty-two technical observers made a total of 50 appraisals, each being made up of repeated assessments of the pleasing or otherwise quality of the television images given by the use of each of the colour response characteristics shown in Fig. 7.

The mean and standard deviations of the marking by the observers is shown in Figs. 8(a) and 8(b).

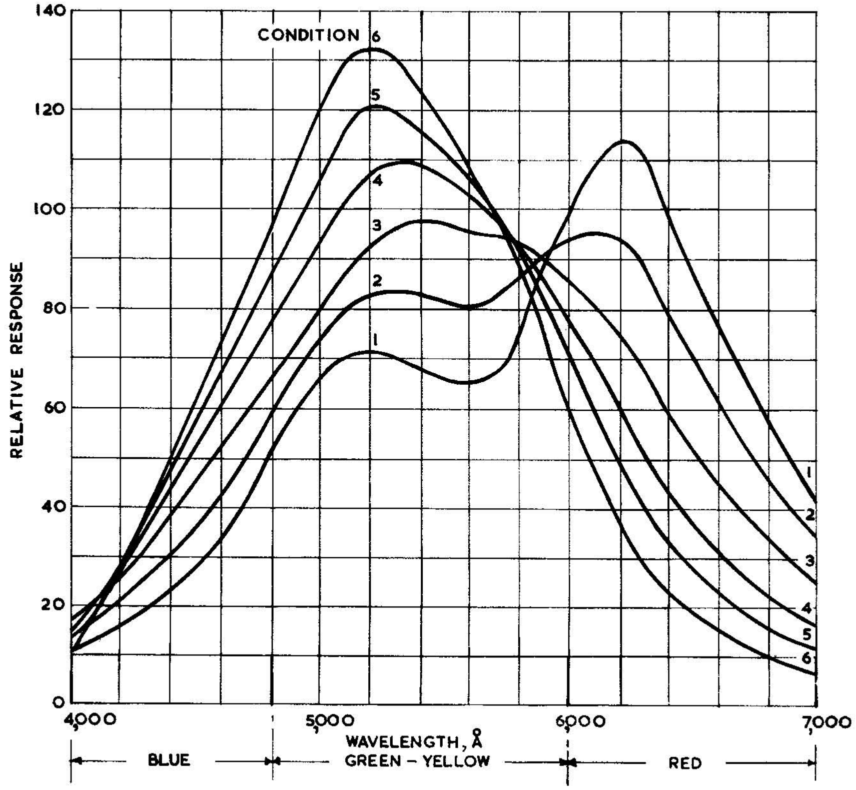
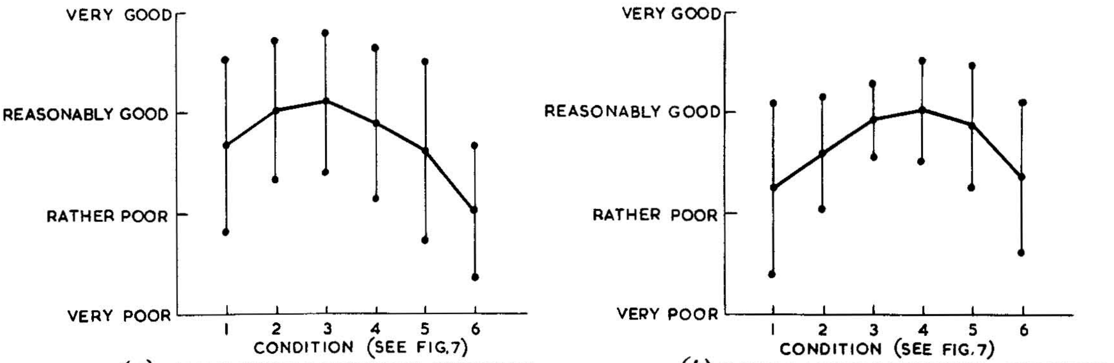
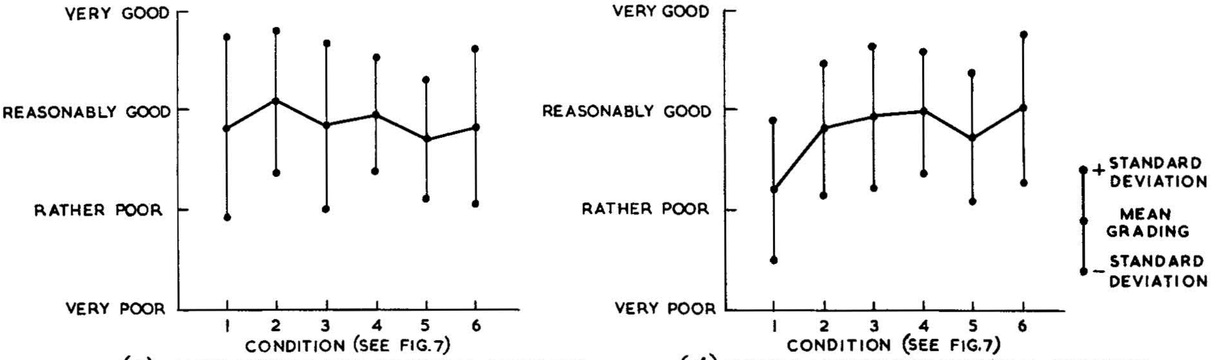


Fig. 7 - Response of image orthicon to tungsten illumination, modified by colour filters



(*a*) MALE MODELS, TECHNICAL OBSERVERS

(*b*) FEMALE MODELS, TECHNICAL OBSERVERS



(*c*) MALE MODELS, NON-TECHNICAL OBSERVERS

(*d*) FEMALE MODELS, NON-TECHNICAL OBSERVERS

Fig. 8 - Preferred colour response for studio television portraiture
(a) male models - technical observers
(b) female models - technical observers
(c) male models - non-technical observers
(d) female models - non-technical observers

Tests were then repeated using batches of the non-technical observers and eighty-nine appraisals were made. The mean and standard deviation of the marking by these observers is given in Figs. 8(c) and 8(d).

Examination of the results from the two groups indicate:

(a) That technical observers are more critical of colour response than their non-technical colleagues.

(b) That the latter have no distinct preference for any of the response characteristics used in the appraisal.

(c) That the technical observers' preferences lie on a very flat curve and are by no means pronounced.

(d) That the preferred colour response for men not having makeup is only very slightly different from that for women models with makeup.

For portrait work generally, a rather vague optimum lies between conditions (3) and (4) (which are indicated in Fig. 7) and this is a condition of slightly less sensitivity to "reds" than that of the typical camera, since condition (3) is the P.822 tube No. 8565 unmodified by filters. The difference in mean rating is however so slight that it is very doubtful whether the inclusion of a colour filter to modify the response could ever bring about an improvement sufficient to offset the disadvantage of the additional flare which is inevitably associated with extra air-to-glass surfaces.

From the results so far described, it would seem that viewers, particularly those without technical knowledge of the subject, are prepared to accept quite a wide range of colour response characteristics as giving a fair reproduction of the original, even when the latter is available for visual comparison.

7. RESPONSE OF THE TELEVISION CAMERA TO COLOURED PAINTS FOR SCENERY AND PROPERTIES

7.1. Specified Equivalent Neutral Values for Paints

It has long been recognised that an unfortunate selection of paint or dyestuff for television scenery may give rise to unexpected results. There have been occasions on which a design or feature in the scenery has completely failed to appear in the television image because the visual contrast with a surround had been obtained by colour rather than by luminance, but much useful work in avoiding these difficulties has already been undertaken in B.B.C. Studios by A.G. Warren and others.[5] Here a series of standard coloured paints is used in making scenery, and each paint has been allocated an equivalent neutral value by means of an "average" television camera. Samples of each colour were compared with individual steps of a neutral grey reflectance step-wedge until a step was found which gave an output signal equal to that of the colour samples. Duplicates of the neutral step-wedge have been made available to scene designers and others concerned, so they are able to make a fairly accurate assessment of the luminance with which any given specimen will be portrayed in the television picture. The inherent difficulty is, of course, that where the response of individual television cameras differs from that used in the original test, there will be departures from the expected reproduction. The degree of error will be a function not only of the variation of colour response in the camera concerned, but also of the spectrum of the light reflected by the paint. Narrow-band saturated colours, particularly vivid reds and yellows, are more susceptible to error than wideband (desaturated) pastel shades, since comparatively minor variations at the "red" end of a camera response may embrace the whole of the relatively small passband required for such a colour. This will give rise to matching difficulties in cutting from one camera to another.

It was found that the satisfactory reproduction of coloured paint and dyestuff sets the camera a much more difficult task than reproducing flesh tones or natural outdoor scenery; indeed there seems little doubt that colour response matching difficulties encountered in portraiture are more likely to be due to narrow-band pigments in the makeup materials than to the human skin tones which they are intended to enhance.

The question which arises is the degree of importance which should be attached to the ability of a camera to reproduce narrow-band pigments. It could be argued that the employment of these paints is under the control of the camera user and that unsuitable colours (e.g. saturated red and orange) should be avoided in making studio scenery. Perfect verisimilitude of colour in a studio set designed for black-and-white television is perhaps something of a luxury, but there are many cases where direct control of colour is not, in fact, with the user: a simple example lies in clothing hired for television purposes but normally used in live stage productions. Nevertheless, an insistence on very close tolerances for the camera colour response, simply to deal with a particularly "difficult" paint, would be uneconomic. It was felt that the determination of a camera response to give the most satisfactory reproduction of a whole range of paints could be unduly influenced by one individual colour, and therefore a somewhat different technique was necessary in making the subjective appraisal. The observers were asked to name those colours which the camera failed to reproduce acceptably: if any particular colour gave rise to complaints which continued throughout the range of colour responses examined, it could be taken to indicate a "difficult" subject.

7.2. The Reliability of Subjective Judgements

In the earlier tests, where the subject matter consisted of natural outdoor scenes or close-up portraiture, an instruction to the observer to score the results on the basis of "accuracy of reproduction of the coloured original" was found to be unambiguous: this was not so in the case of coloured paints.

During pilot tests in which the television camera reproduced samples of paintwork, some non-technical observers appeared to wish to relate the brightness of the equivalent grey level wholly to the emotional impact made by the hue of the paint sample, while some of the technical observers seemed anxious to give the "right" answer and were clearly, if subconsciously, bringing their memories of relative luminances to bear on the assessments made.*

It was therefore decided to carry out a preliminary investigation into the subjective impressions made by the paint samples viewed by eye directly and, in order to help standardize the observers' interpretations of what they were required to assess, a grey scale was included in the test material using the standard series of scenery paints. Twenty samples of different coloured paintwork were prepared each 4 in × 4 in (10 cm × 10 cm). These were arranged in a group and displayed simultaneously, illumination being by means of studio-type tungsten illumination. Five of the paintwork samples formed a grey scale (white, black and three intermediate greys) and each observer was first asked to allocate numerical values to the intermediate greys, white having been arbitrarily rated 1 and black 10. The observers were then, in a carefully worded question, asked to relate each of the other colours to the numerical grey scale which they had thus already chosen.

The object of the experiment was to determine the reliability of the observers' judgements of a suitable equivalent neutral value for each of the coloured paint samples. Examination of the grey scale selected by each observer showed that there was close grouping of what might be termed "personal gamma", since more than 60% of the observers allocated numbers to the neutral grey samples which, when plotted against measured luminance, showed very close agreement with curves lying between $\gamma = 0\cdot3$ and $\gamma = 0\cdot4$. Only 16% of observers gave answers which do not lie on a smooth curve.

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*The vehemence with which observers defended their assessments in discussion afterwards was particularly noteworthy. This is clearly one of those subjects in which few will admit to fallibility!

In plotting each observer's assessment of each colour patch in terms of the neutral scale, account was taken of each one's particular grey scale judgement, and before being included in the results they were, in effect, "gamma-corrected" to a standard value of $\gamma = 0{\cdot}33$ which has been shown to be typical[6,7] at the brightness levels used in this experiment. It was thus possible to compare individual's assessments of the selection of coloured paints in terms of a common scale of neutral grey luminosities.

To a limited extent this was a repetition of attempts to determine a "photopic curve" of relative luminances by comparison of colours with a neutral grey scale and the results obtained clearly underline the unsatisfactory nature of such an experiment. One particular paint sample (Signal Red) was, in comparatively few observations, allocated every equivalent neutral value on the scale from 1 to 10, but other colours were given remarkably consistent evaluations. Where the sample was of a wide-band desaturated colour the observers agreed closely on its equivalent neutral value, but in cases of narrow-band, vivid colours, the judgements given showed a marked divergence of opinion. The spread of opinions in the latter case was, however, clearly not attributable to indecision: many observers were convinced of the accuracy of their judgements but were, apparently, influenced in different ways by factors other than luminance.

The results of this preliminary test were consistent with the hypotheses,

(1) that where it is desired to represent colours in a scene by means only of a neutral grey-scale, individual opinions of the correct neutral-value are not based simply on the relative luminances of the colours, but are influenced by the saturation and/or hue of the colour and,

(2) that diversity of opinion on the equivalent grey of a colour usually increases with the saturation of that colour.

The results are shown graphically in Fig. 9, the paint samples having been matched to the Munsell Book of Color[8] to obtain recognised assessments of the saturation ("Chroma" in the Munsell system) and relative luminance ("Value" in the Munsell system) of each of the colours used. The mean equivalent neutral rating given by the observers is shown, together with standard deviation. Munsell "Value" rating for each paint was approximately translated into the same arbitrary neutral scale as that used by the observer, and is also shown in Fig. 9. In Table 1 the standard deviation of the observers' rating of the equivalent neutral value is shown against Munsell's "Chroma" for the paint samples. This indicates that, apart from one particular colour (lime yellow) there is a fairly high degree of correlation (the correlation coefficient is 0·66) existing between diversity of opinion and the saturation of the paint sample. The peculiarity of the case of lime yellow is not easily resolved in the simple experiment conducted here with comparatively few observers: it seems possible that an accidentally favourable combination of adjacent colours made it easy for the observers to agree on this particular sample.

A conclusion to be drawn from this somewhat digressive experiment is that when saturated paints are employed to determine colour responses in a television camera, the results must be accepted only with the greatest caution since individuals are far from unanimous in what they consider a good result to be.

TABLE 1

Colour	Munsell Chroma	Standard deviation of brightness estimates
Signal Red	11	1·79
Orange	10	1·41
Canary Yellow	9	1·18
Lime Yellow	9	0·84
Pink	8	1·09
Sand Yellow	7	1·00
Light Green	7	0·99
Sky Blue	5	1·17
Violet	4	1·11
Light Khaki	4	0·98
Pale Blue	4	0·82
Deep Green	4	0·77
Deep Khaki	4	0·75
Mid Blue	4	0·74
Green	3	1·07
Light Brown	3	1·00

Correlation of Standard Deviation of Observers' Rating with Munsell's Chroma

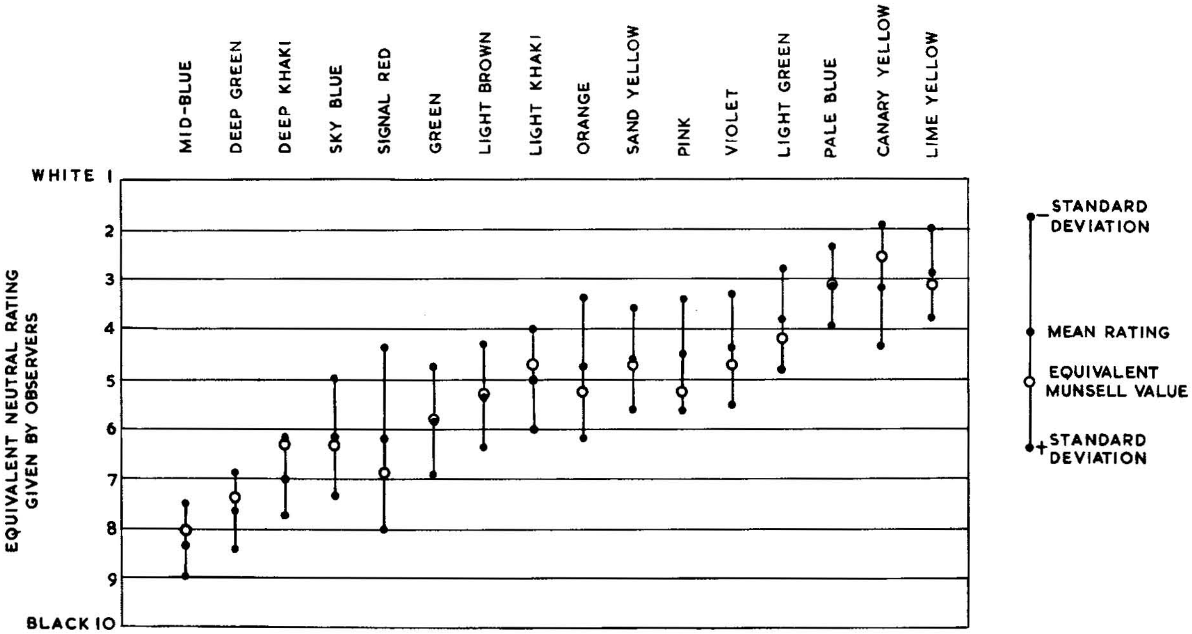

Fig. 9 - Observers' assessment of luminance

7.3. Preferred Response to Studio Scenery Paints

As a result of the direct visual assessments just described, a modification was made to the technique adopted when seeking the observers' appraisal of camera response to the display of coloured paint samples. Instead of being asked to award marks for the general acceptability of each condition, the observers were asked to state which colours they considered to be wrongly reproduced by the television camera when it was given, in turn, each of the six colour response conditions shown in Fig. 7. In this way the colours which were now known to be "difficult" subjectively could, if necessary, be disregarded or weighted less than those desaturated colours on which there was general agreement in the direct-viewing experiment. The results for twenty-five skilled observers is given in Fig. 10. Curve (a) shows the average number of colours criticised for each of the six conditions when all the paint samples were included and Curve (b) shows the number of criticisms remaining after three "subjectively difficult" colours (Signal Red, Orange and Canary Yellow) had been excluded from the considerations. It will be seen that the optimum again lies on a rather flat curve which peaks, as in the other tests, between conditions 3 and 4.

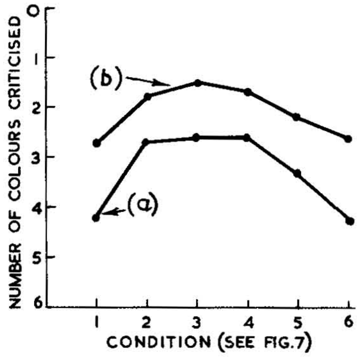

Fig. 10 - Average number of colours criticised by observers (a) taking into account criticisms of all colours (b) ignoring criticisms of signal red, orange and canary yellow

8. OPTIMUM COLOUR RESPONSE

The results of the three investigations into preferred response for the outdoor television, studio portraiture and scenery paint reproduction can all be interpreted to indicate a preference for a colour response approximating to what may be termed condition 3½ in the system of arbitrarily chosen responses shown in Fig. 7. In no case is the preference very marked, and considered from the point of view of reproduction by a single camera which is not required to match the black-and-white versions produced by other cameras, it would seem that any response lying between the limits of condition 2 and condition 4½ would probably be satisfactory. Nevertheless, it is necessary to select one particular response as the mid-point upon which tolerances can be specified for camera-matching purposes and condition 3½ is recommended as that point.

Thus, the optimum colour response for black and white television reproduction is as shown in Fig. 11 where, for comparison, the internationally agreed curve

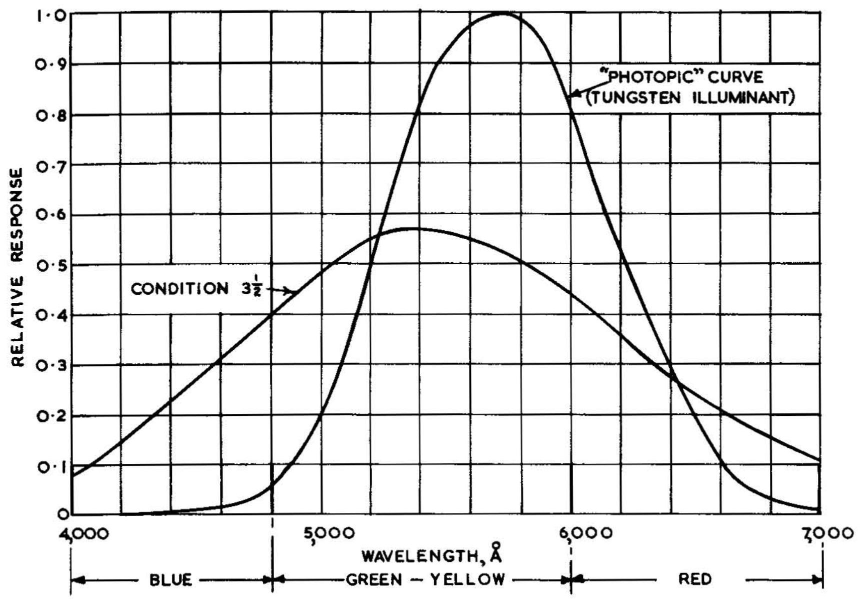

Fig. 11 - Optimum colour response (to tungsten illumination) for a black and white television camera

of relative luminances for photopic vision is also plotted on the same co-ordinates. It will be remembered that this result refers to a television camera under tungsten illumination, and where it is desired to specify the response of a camera tube alone, it is usual to quote the response to an equi-energy stimulus. This is given in Fig. 13. The wavelength at which the maximum response occurs has moved from the green-yellow region to the blue region because equi-energy illumination contains relatively more blue light than tungsten illuminant.

9. LIMITS OF ACCEPTABILITY FOR COLOUR RESPONSE

It was expected that a separate experiment would be necessary to fix limits of acceptability for colour response, since the sudden changes in apparent luminance of an object which might occur on switching from one camera to another are generally considered to be more noticeable than equivalent departures from the preferred colour response in any single camera. Moreover, the visibility of such changes will be a function of the grey-scale luminance levels at which they occur, and the colour of the original object has no direct bearing on the result.

It was decided to use a display of paint samples as the subject matter since this gave a representative selection of reproduced grey levels in random relative positions and a number of special colour filters were made up to give conditions 1, 2, 3, 3½, 4, 5 and 6. This time, however, accurately selected neutral-density filters were bound up with them, so that each combination caused the image orthicon No. 8565 not only to have the desired colour response but also to have a standard signal output level for "white" without readjustment of any gain control. The filters were mounted on a mechanical-slide device positioned in front of the camera lens and so contrived that very rapid changes could be made from one condition to another. The arrangement was slightly more difficult to implement than one having two separate cameras with video switching from one to the other, but it had the advantage that the viewpoint remained constant.

The observers were shown a television reproduction of the display of paint samples by the camera having, firstly, a colour response corresponding to condition 3½ and then changing as near instantaneously as possible to some other condition. As many alternations as the observer wished were made between the two conditions until he was satisfied that significant changes were, or were not, taking place in the luminance of the reproduction of one or more paint samples.

This, it was felt, was a fairly rigorous test, but not an unreasonable one, since occasions must frequently arise in which standard colours are seen in an unfortunate juxtaposition and draw attention to inequalities in camera colour response.

The percentage of observers able to see the effect of a rapid change from condition 3½ to other conditions is given in Fig. 12. Interpolation on this curve indicates that a change of one whole condition (from 3½ to 4½) would be noticeable to nearly 80% of the observers but a change from condition 3½ to condition 4 was detected by less than 50% of observers.

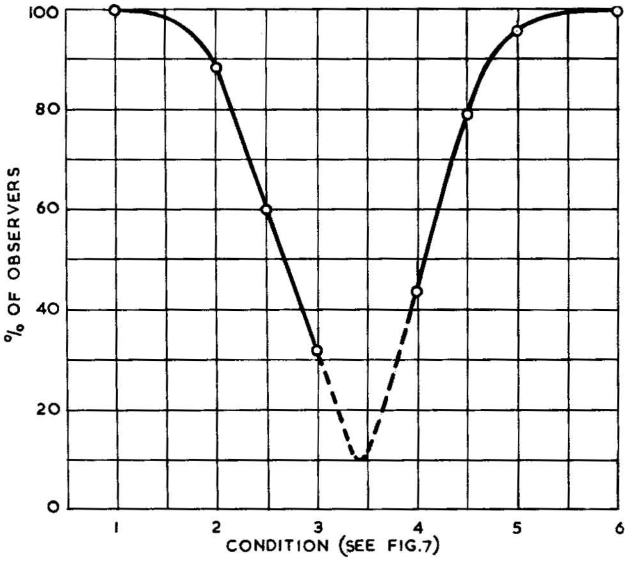

Fig. 12 - Percentage of observers able to see a rapid change from condition $3\frac{1}{2}$ to other conditions

The setting of limits of acceptability is clearly one of arbitrary choice since the experimentally determined visibility of changes in luminance will inevitably be a function of the precise method of test, but the results in Fig. 12 are a useful guide to a reasonable choice of tolerances. It should be stated here that the changes in luminance noted by the observers invariably concerned paint samples whose spectra were predominantly at the "red" end of the visible spectrum. This is explained by the fact that the changes made from one condition to another represent a "tilt" of the colour response characteristic in which the alterations of luminance were greater for "reds" than for "blues". It will be noted from Fig. 7 that the change from condition 3½ to condition 4 represents a decrease of about 15% in luminance at each wavelength above 6,000 Å, similarly, condition 3 has luminances about 15% greater than those of condition 3½ over the same band. Now these changes were noticeable only to about 40% of observers under favourable conditions, but, since two adjacent cameras might well be on opposite limits of acceptability, it is thought that ± 15% could, in the first instance, be taken as the tolerances of departure from the preferred response at any point in the range 4,300 Å to 7,000 Å.

It should be noted that the 15% tolerance is not a proportion of peak amplitude, but is a proportionate variation from the height of any ordinate of the preferred colour response curve after normalization to "white" light. This is in accord with the Weber-Fechner law that for equal visibility of change, $\delta B/B$ remains constant, where B is the brightness.

10. RECOMMENDATIONS

It is suggested that the preferred colour response for a television camera tube when measured with equi-energy illuminant, should be in accordance with the curve of Fig. 13. This is the "condition 3½" response converted to that for an equi-energy stimulus as usually employed in specifications.

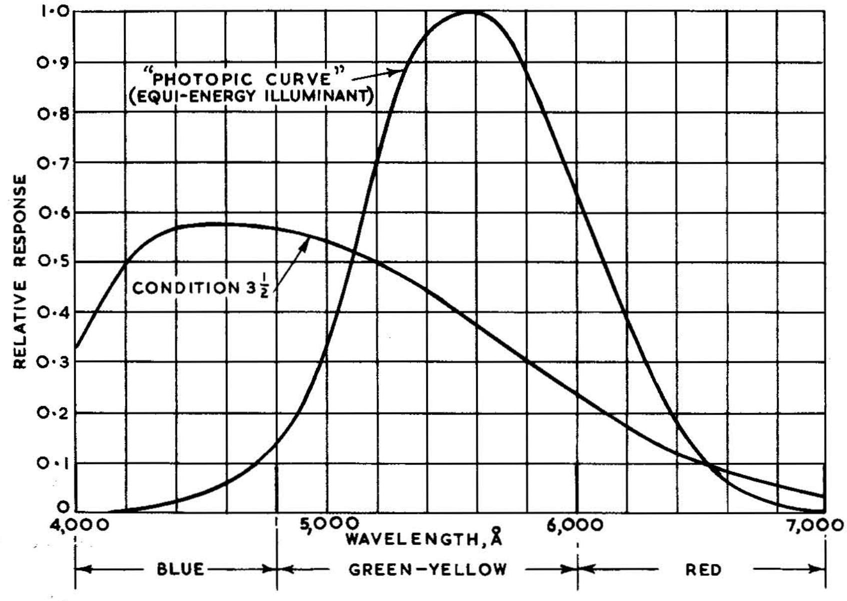

Fig. 13 - Optimum colour response (to equi-energy illumination) for a black and white television camera

In order to decide the acceptability of tubes which have responses dissimilar in some respects to the above, the criterion should be that they match a tube of preferred response sufficiently well to permit indiscriminate cutting from one camera to another on all except very saturated colours.

It is suggested that this requirement will be met if, after its colour response curve has been normalized for output level to "white" (i.e. equal area under the curve) all ordinates are within ± 15% of the corresponding ordinates of the preferred response shown in Fig. 13.

It is also suggested that scene designers and makeup artists can assist materially by avoiding highly saturated, vivid colours. If a pastel colour can be selected to give the same black-and-white result, it seems virtually certain that all normal image orthicons will reproduce it without creating any camera matching difficulties.

11. ACKNOWLEDGEMENT

The writer of this report wishes to acknowledge that the experimental work for this investigation was carried out by his colleague Mr. W. Rhodes.

Mr. Rhodes devised the experimental apparatus required, computed and measured the colour filters and colour responses, and analysed the results of the very large number of subjective tests which he conducted.

12. CONCLUSIONS

It is feared that the reader may now share the author's view that the experiment has to some extent proved more arduous than instructive. However, the fact that an optimum response is only vaguely defined, and is found to lie on a very flat preference curve, may serve as a warning against drawing too many conclusions from a single observation. The tolerances to be placed on tubes are clearly dependent on the degree of assurance required that no colour or fortuitous combination of colours will give rise to noticeable luminance matching errors, and the values suggested can only be a starting point for negotiation with the camera-tube manufacturers.

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